Tropospheric Emission Spectrometer
EOS CAN Workshop

August 15, 1996

Jet Propulsion Laboratory

Purpose

- DEFINE TES
- FEASIBILITY ASSESSMENTS RELATED TO THE DEVELOPMENT OF LOW COST DERIVATIVES OF EXISTING SATELLITES FOR EARTH OBSERVING MISSIONS /CAN5-52808-308

Agenda

- TES Science
- TES Project Organization
- TES Instrument Design
- TES Instrument Resource Requirements
- TES Development Schedule

TES Science

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Primary Objective

- To determine, through a combination of measurement and modeling, the global distribution of tropospheric ozone and its sources and sinks.

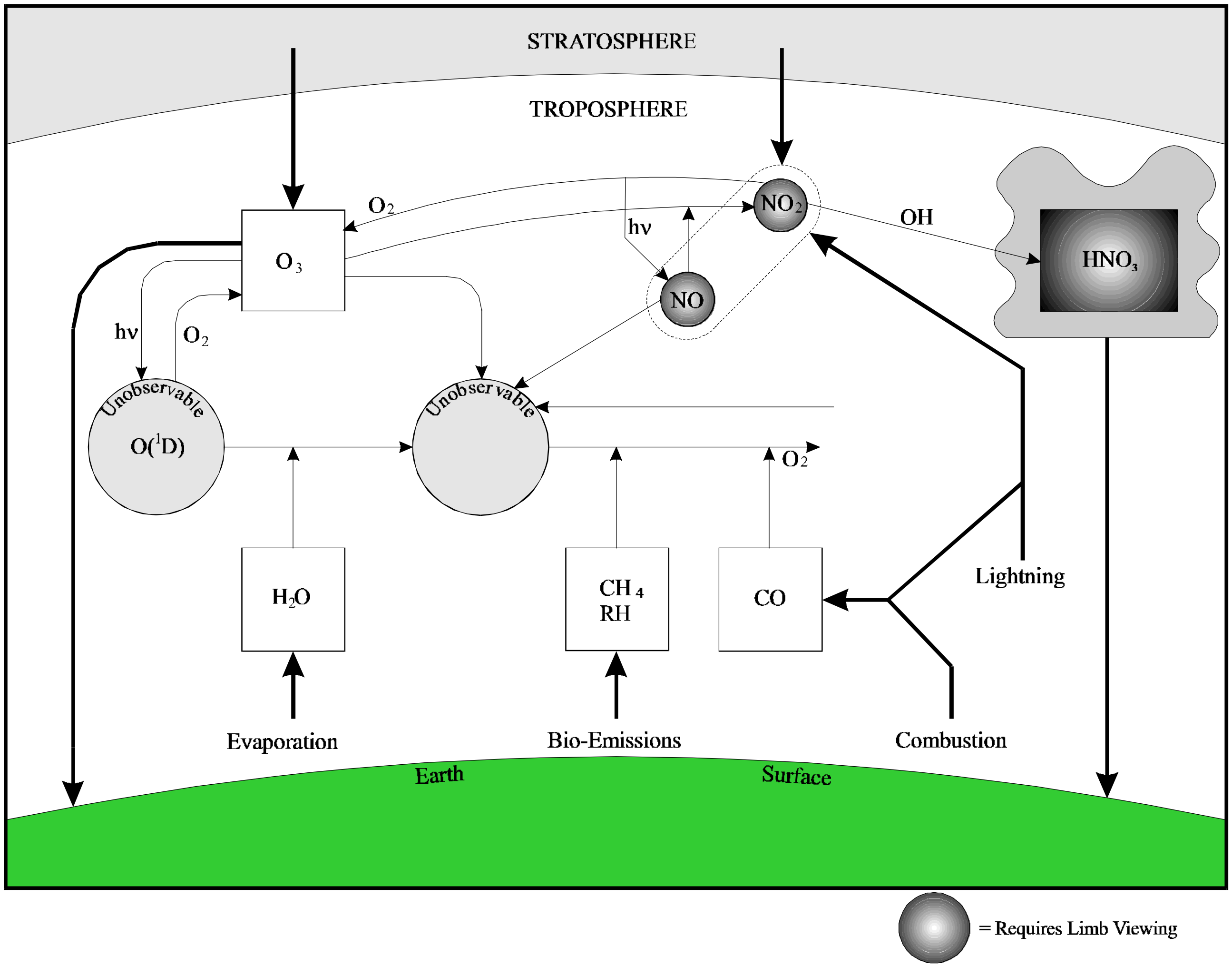
Tropospheric Ozone and its Precursors

- Knowledge of the origin and fate of tropospheric ozone (O3) is critical for several reasons:
  - it is the primary source (through photolysis by solar UV radiation) of hydroxyl radicals (OH) which, in turn, provide the mechanism by which pollutants such as carbon monoxide (CO) and methane (CH4) are removed from the lower atmosphere;
  - through its reactions with hydrocarbons, ozone is the source of PAN (peroxyacetylnitrate), a major ingredient of urban phochemical smog (it is what makes the eyes water on smoggy days);
  - ozone itself is hazardous to the health of both plants and animals since it is a powerful oxidant.
- Thus while *some* tropospheric ozone is essential for human health, too much is deleterious (the EPA allowed maximum is 105 ppbv for any 1 hour per day).

Tropospheric Ozone and its Precursors

- The sources of ozone are two-fold: some is transported down from the stratosphere (the exact amount being controversial) and some is created *in situ* through the photolysis of nitrogen dioxide (NO2) to nitric oxide (NO) which, in turn, reacts with CO and hydrocarbons to form O3. The sum of NO + NO2 is termed NOx and its presence is essential for ozone formation. Note that the NOx is not consumed in this process (i.e., it is catalytic) and becomes available for further ozone production. Thus urban areas, where combustion and automobile exhausts provide prolific sources of NOx, are particularly prone to atmospheric pollution (especially in areas of abundant sunlight). However, many rural areas (for example, the southeastern US) occasionally fail the EPA standard for reasons that are somewhat mysterious. Finally, the sink of NOx is nitric acid (HNO3) which is rained out to the surface (and is, incidentally, a component of acid rain).
- In order, therefore, to understand tropospheric ozone, one must do more than just measure O3 itself - it is essential to make co-located measurements of NOx, HNO3, CO and hydrocarbons (of which CH4 is by far the most abundant) on a global scale because atmospheric pollution is no respecter of political boundaries.
- This is the policy issue that TES has been designed to address.

Tropospheric Ozone and its Principal Precursors

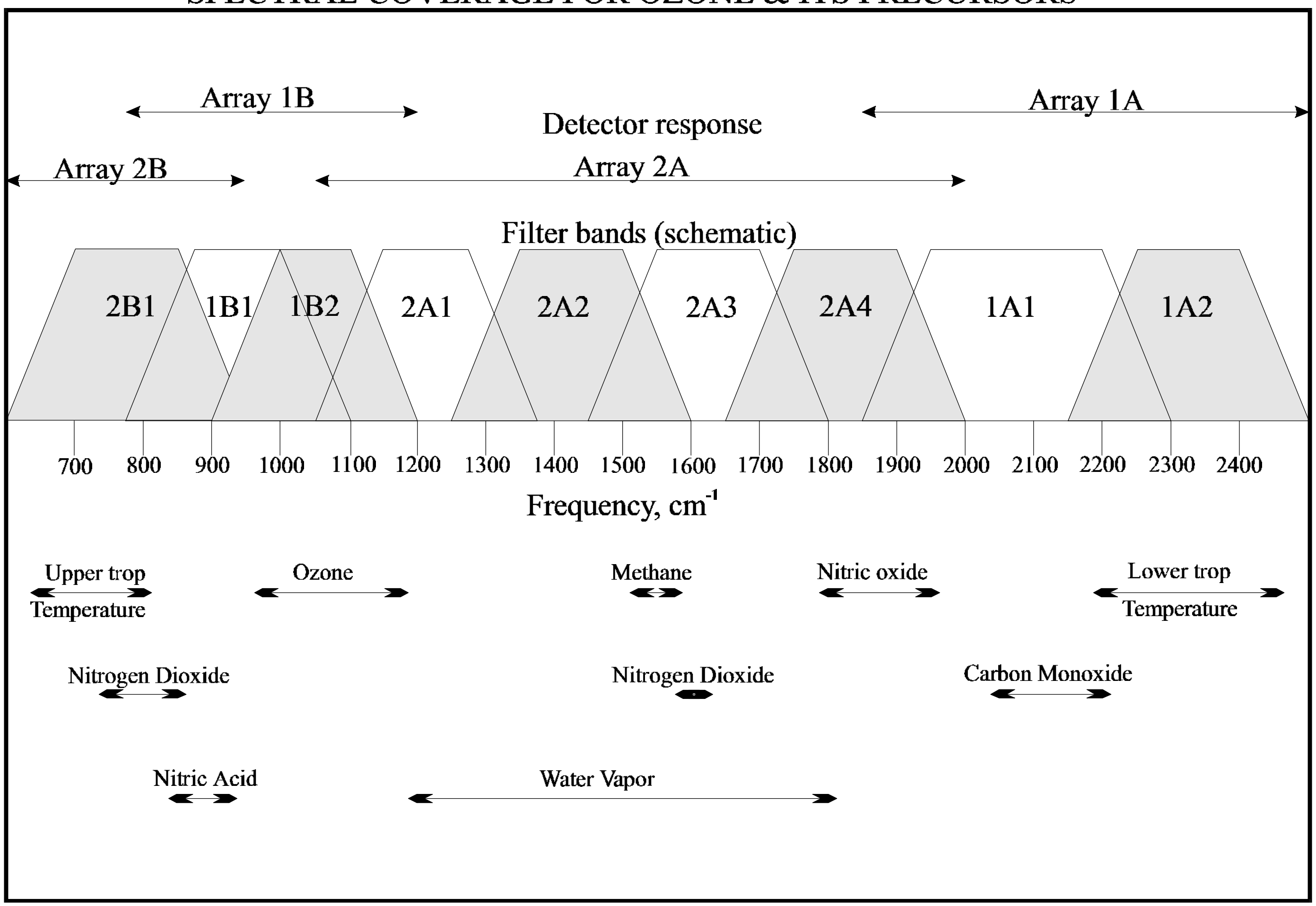


Measurement Requirements

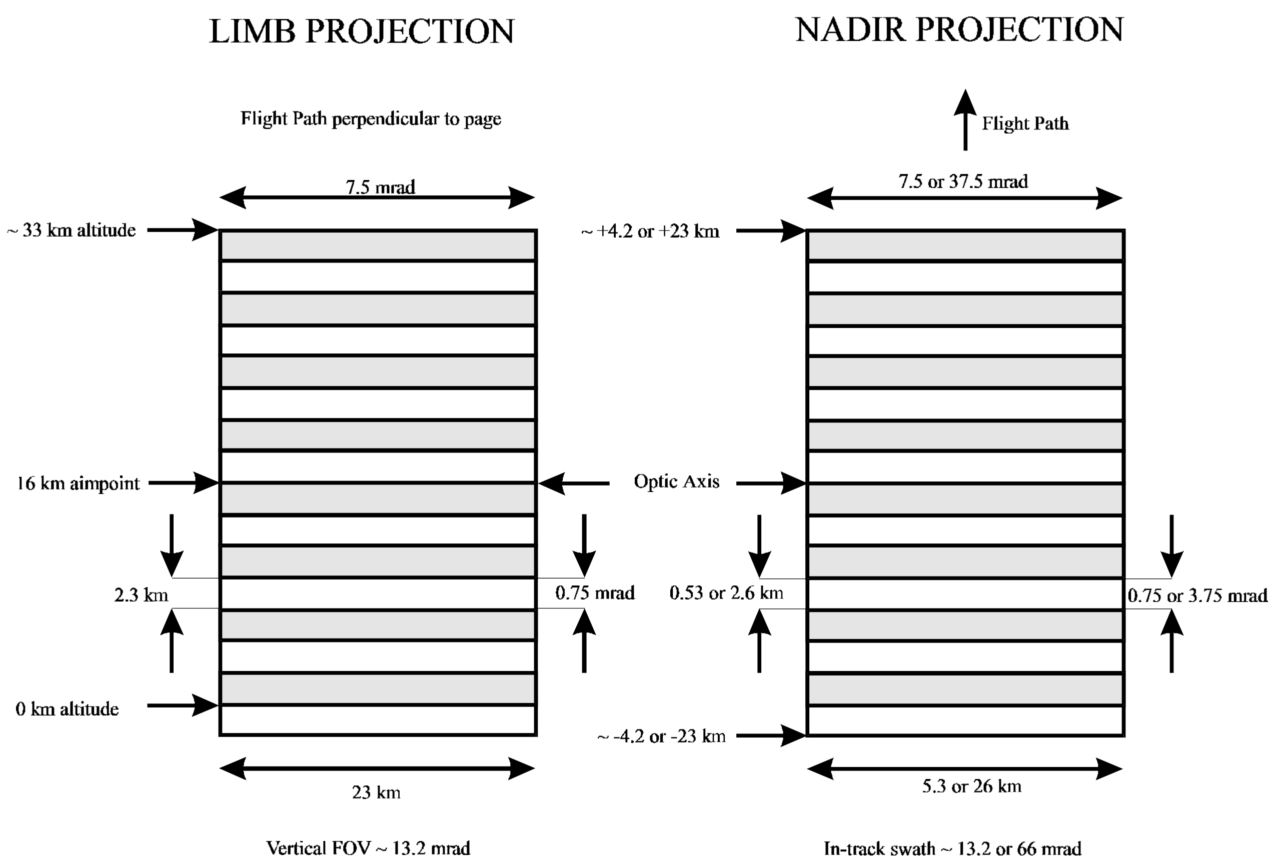
- The infrared signatures of certain critical species (particularly NO, NO2 & HNO3, collectively known as NOy) are very weak and, indeed, are invisible to nadir sounders. Only limb sounding can provide the necessary sensitivity. However, limb sounding rarely penetrates below 4-5 km altitude (because of clouds). Fortunately, many of the other important species (including ozone itself) can be measured by nadir viewing with a far higher probability of reaching the surface.
  - Accordingly, TES must be able to acquire data both in nadir and at the limb
- The spectral features of the species to be measured are widely distributed throughout the infrared.
  - Accordingly, it has been determined that TES must be capable of making measurements between 650 and 3050 cm-1 (3.3 - 15.4 µm)
  - This range is too wide for any one detector technology to cover. Accordingly, the range has been split into 4 sub-regions in order to optimize the detector arrays. This also permits better background control (i.e., better SNR) and, through the use of an appropriate optical configuration, 4 spectral bands to be observed simultaneously.
  - Spacecraft move very quickly, so in order to preserve an associated requirement that measurements, as nearly as possible, be made on the same airmass, it has been decided that TES must be equipped with 1 x 16 arrays of detectors (i.e., at the limb, 16 altitudes are measured simultaneously).

TES Spectral Coverage Requirements

SPECTRAL COVERAGE FOR OZONE & ITS PRECURSORS



TES Footprint



TES detectors projected to the nadir and to the limb

Measurement Requirements

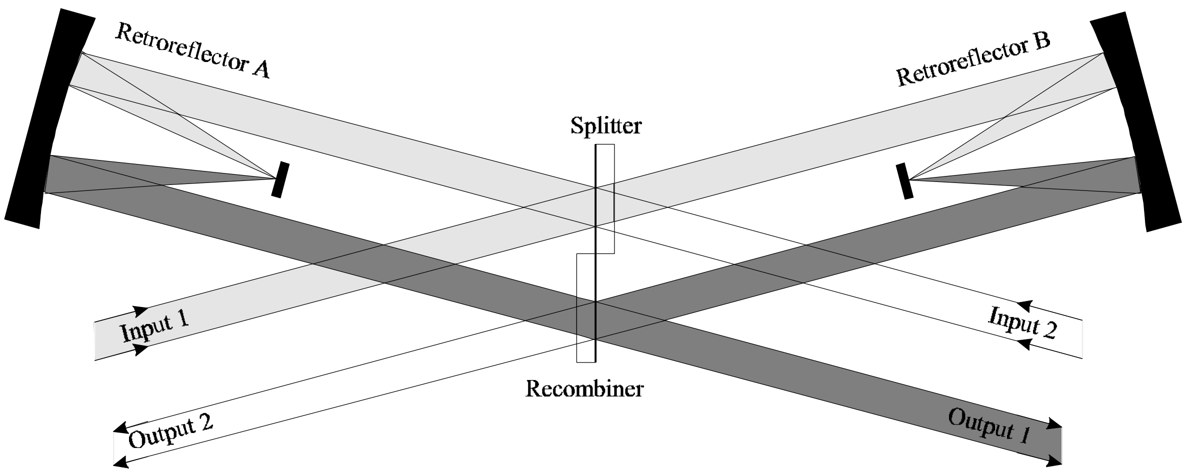
- It is a property of spectral lines that, in the troposphere, the widths of the features is about 0.1 cm-1 near the surface and about 0.025 cm-1 near the tropopause *independent of species and frequency.* It is readily shown (*via* the Optimum Filter Theorem) that the best discrimination of features is achieved when the spectral resolution matches the linewidths.
  - Accordingly, it has been decided that TES shall provide 0.1 cm-1 resolution when downlooking and 0.025 cm-1 when limb-viewing.
- Only one class of instrument provides both wide frequency coverage and frequency-independent spectral resolution - a Fourier Transform Spectrometer (FTS).
  - TES will be an FTS

HOWEVER

- The character of an FTS is such that it MUST be used in a staring mode (no push-broom or whisk-broom acquisitions).
  - Thus the pointing jitter requirements for TES are quite severe - 75 μrad peak-to-peak over any 16 second interval. This corresponds to about 250 meters at the limb.

Connes Interferometer

Layout of the Connes'-type (4-port) Interferometer



NOTE: Retroreflectors shown as cat's-eyes because corner reflectors are difficult to show in a 2-dimensional drawing

Performance Requirements

- Performance Requirements for TES were codified by a workshop held at the Goddard Institute for Space Studies (NY) in November 1995.
  - The current TES design meets these requirements, but with an uncomfortably small margin. Further modifications would render TES unacceptable to the scientific community.

TES Standard Data Products

(Numbers in brackets are estimate Volume Mixing Ratio sensitivities based on a combination of limb and nadir observations; accuracies are expected to be in the 5 - 20% range)

Altitude coverage is 0 - 33 km except for NO_y.

O_x	H_xO_y	C-compounds	N-Compounds
O_3 (3 ppb)	H_20 (0.5 - 50 ppm)	CO (3ppb)	NO
		CH_4 (14 ppb)	NO_2
			HNO_3

Operating Modes

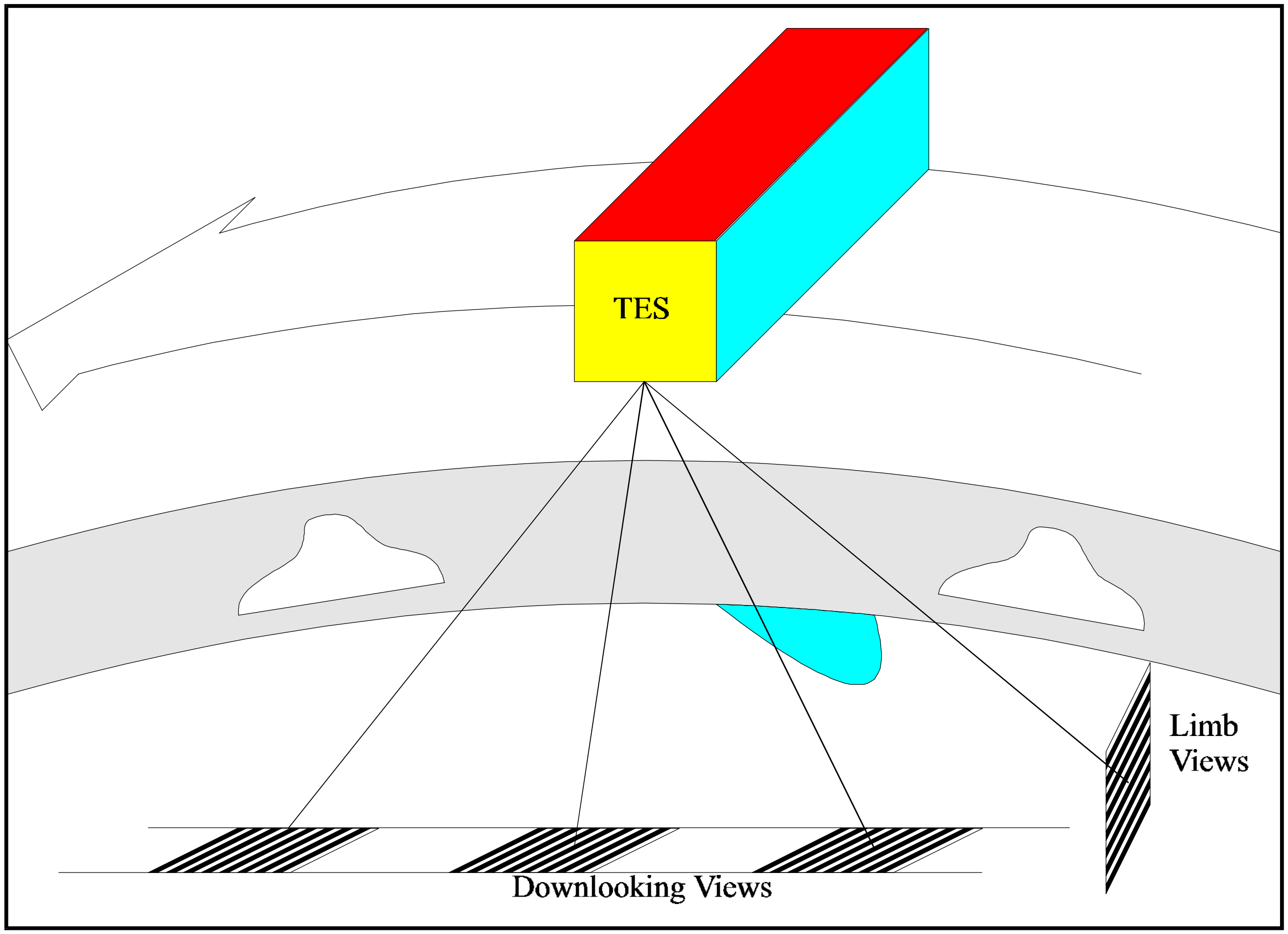
- The two basic operating modes of TES (downlooking & limb) require individual observations of 4 and 16 seconds each.
- TES will make its Global Surveys on a 4-day-on, 4-day-off basis (commensurate with the 16-day orbit repeat period). Sample sequences recur every 80.3 seconds, during which two calibration scans, two nadir scans and 3 limb scans are made. Concatenation of limb and nadir observations is made in subsequent ground data processing.
- During the "off" days, major radiometric calibration data sets will be acquired, plus observations of certain targets of opportunity (e.g. volcanoes - these are so called "special products")

PREFERRED ORBIT FOR TES

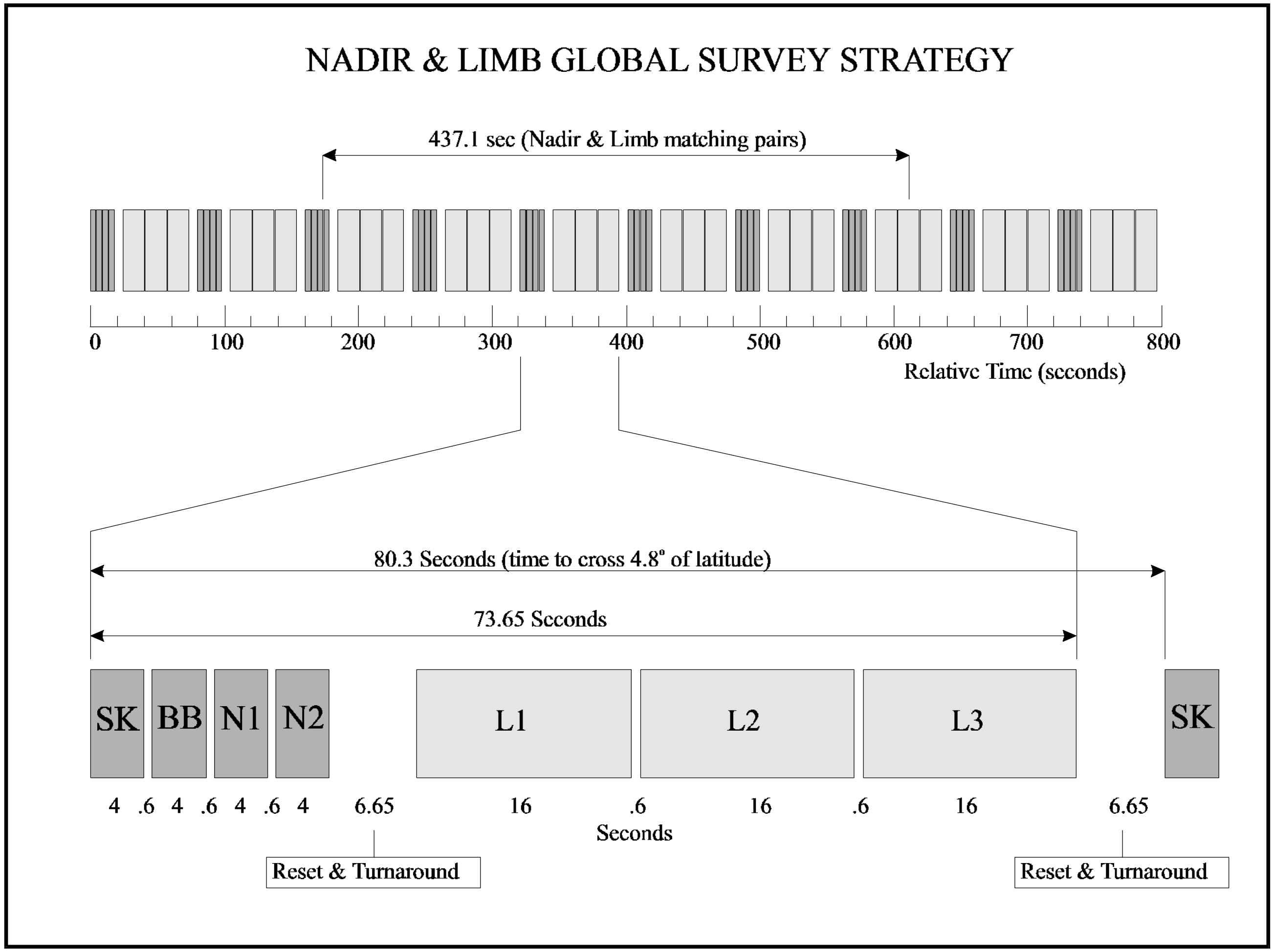
- Because of the reduced cloud cover over land in the morning hours TES prefers an equator crossing time of 10:45 a.m. +/- 15 min

TES Data Acquisition Modes

Cartoon of the TES Data Acquisition Modes



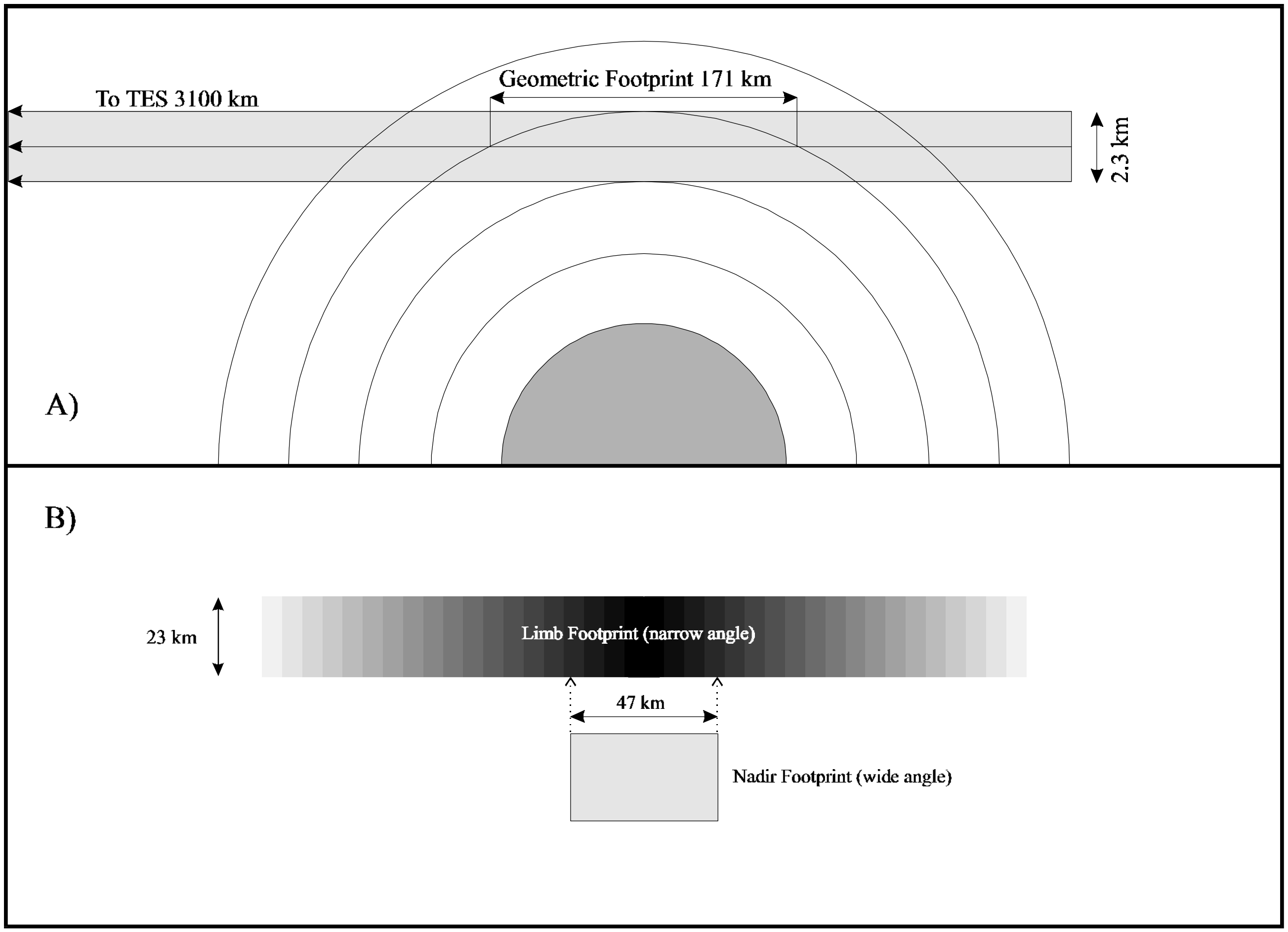
Nadir and Limb Global Survey Strategy



Phasing of Limb and Nadir observations in Global Surveys

Nadir and Limb Views

A) Geometric path length at the limb; B) Concatenation of limb and nadir views in Global Surveys



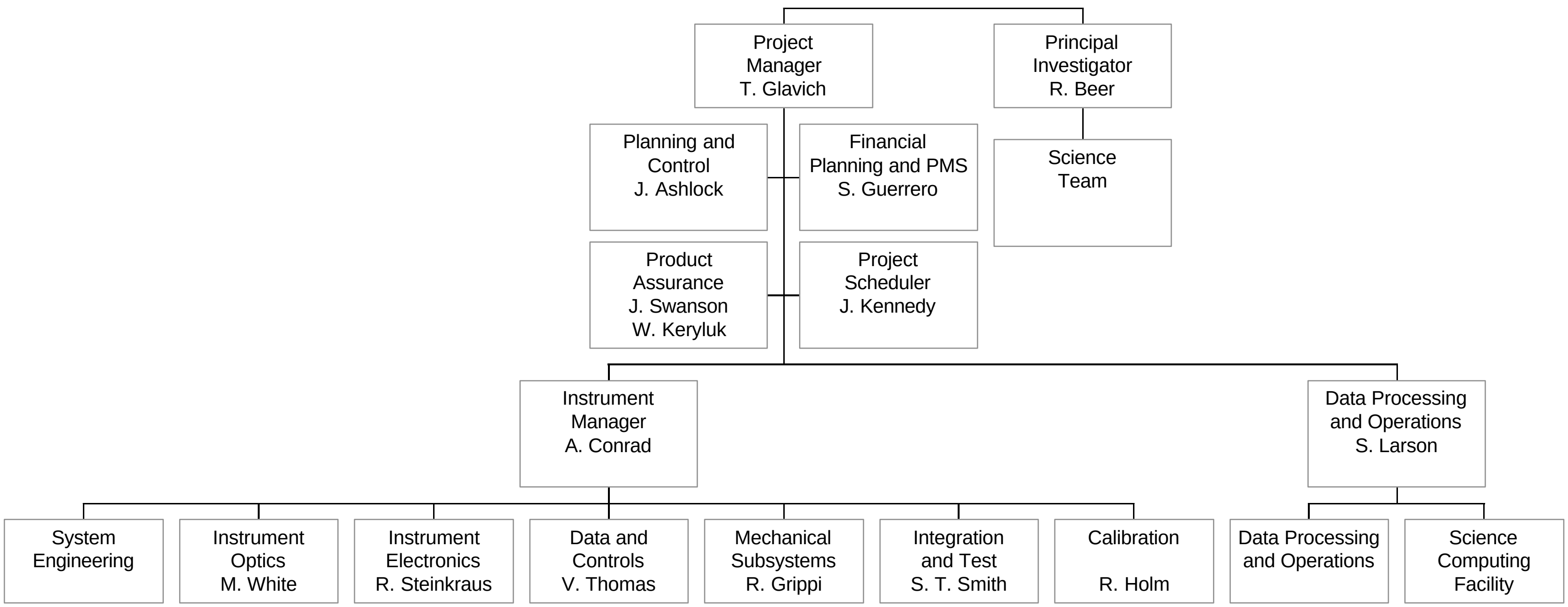
TES Special Data Products

H_xO_y	C-compounds	N-Compounds	Halogen-compounds	S-Compounds
H_2O_2	CO_2	HNO_4	HCL*	SO_2
HDO	C_2H_6	NH_3	HF*	COS
	C_2H_2	HCN	H_2S*	
	HCOH	N_20**		
	HCOOH			
	CH_3OH			
	PAN			

* Volcanic plume column densities only

** Control (VMR known)

TES Project Organization



Instrument Design

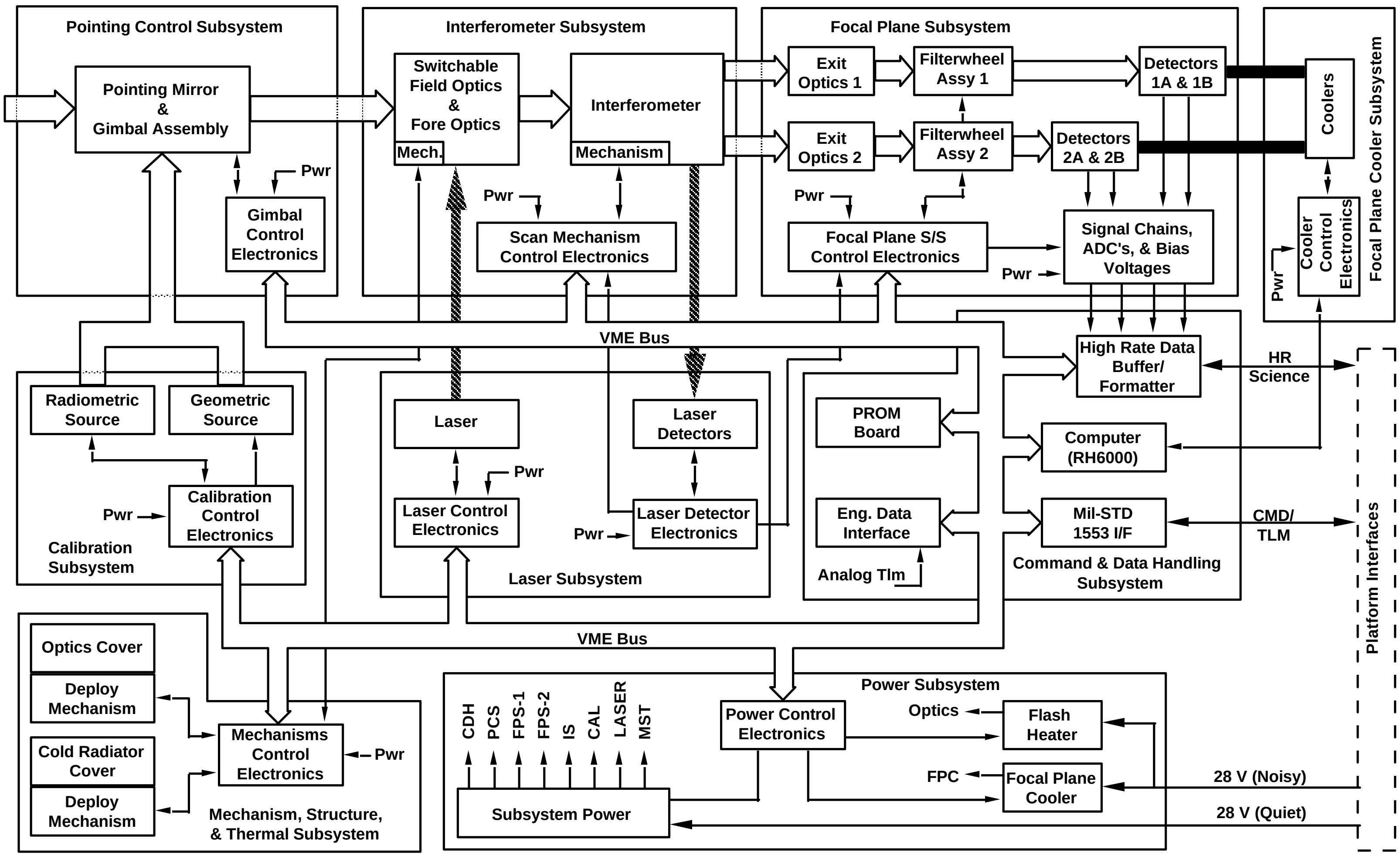
Tom Glavich

Project Manager

TES Science Requirements

Spectral coverage:	650 - 3050 cm^{-1} (3.28 - 15.4 microns)
Spectral resolution:	0.1 cm^{-1} (nadir), 0.025 cm^{-1} (limb)
Spectral accuracy:	±0.00025 cm^{-1}
Spatial coverage:	45^o cone from nadir to -71^o in track
Spatial resolution:	0.75 x 7.5 mrad limb 7.5 x 75 mrad downlooking
Temporal coverage:	Global Map of Standard Products every 8 days
Dynamic range:	cold space to 340 K
Radiometric accuracy:	±1% radiance (NIST traceable)
Signal-to-noise ratio:	Source photon shot noise limited (goal)
Stare Time:	4 sec nadir, 16 seconds limb
Global Coverage:	5 degrees latitude sampling

TES Block Diagram



Design Drivers

- Instrument size is dominated by the interferometer
  - Interferometer size is determined by the spectral resolution and aperture.
    - Aperture is defined by the photon flux from atmospheric black body radiation.
    - Spectral resolution is defined by spectral line shape and width.
- Instrument volume is determined by radiator size.
  - three radiator sets, interferometer, coolers, electronics ..
- Earth shield required to maintain radiator performance

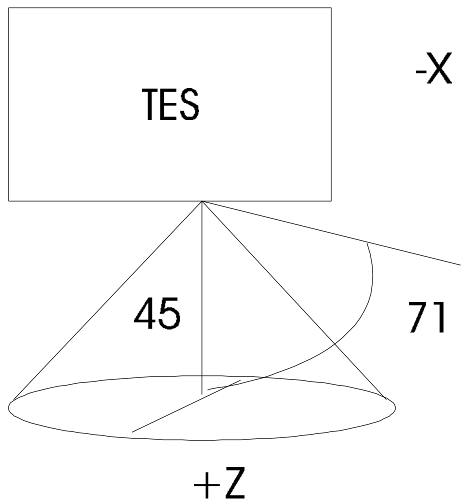
Design Drivers

- Coolers sized to meet focal plane requirements.
  - parasitic heat loads dominate
- Pointing system is required.
  - provides image motion compensation
  - points at : limb, nadir, calibration source,
  - points above limb for cold calibration.

TES Pointing Requirements

- FIELD OF REGARD
  - The Field of Regard shall be that of a 45-degree cone, centered about the instrument + z axis, with an extension to 71 degrees from the instrument along in the instrument -x direction.
- MAGNIFICATION
  - TES shall have two switchable fore-optics, a 1:1 (normal) and a 5:1 (expanded). The field expansion optics shall only be used in the nadir view.
- POINTING COMMANDABILITY
  - The instrument boresight shall be commanding to specific locations defined by latitude, longitude and altitude. For internal calibration, TES shall be commandable to a view of the alignment and radiometric calibration sources.

TES Field of Regard



TES Fields of View

Field	*Pixel Field of View*	*Array Field of View*
Limb	0.75 x 7.5 mrad	12 x 7.5 mrad
	2.58 x 25.8 arcmin	41.4 x 25.8 arc min
	0.043 x 0.43 deg	0.69 x 0.43 deg
Nadir (narrow angle)	0.75 x 7.5 mrad	12 x 7.5 mrad
	2.58 x 25.8 arcmin	41.4 x 25.8 arc min
	0.043 x 0.43 deg	0.69 x 0.43 deg
Nadir (wide angle)	3.75 x 37.5 mrad	60 x 37.5 mrad
	12.9 x 129 arcmin	206 x 129 armin
	0.21 x 2.1 deg	3.4 x 2.1 deg

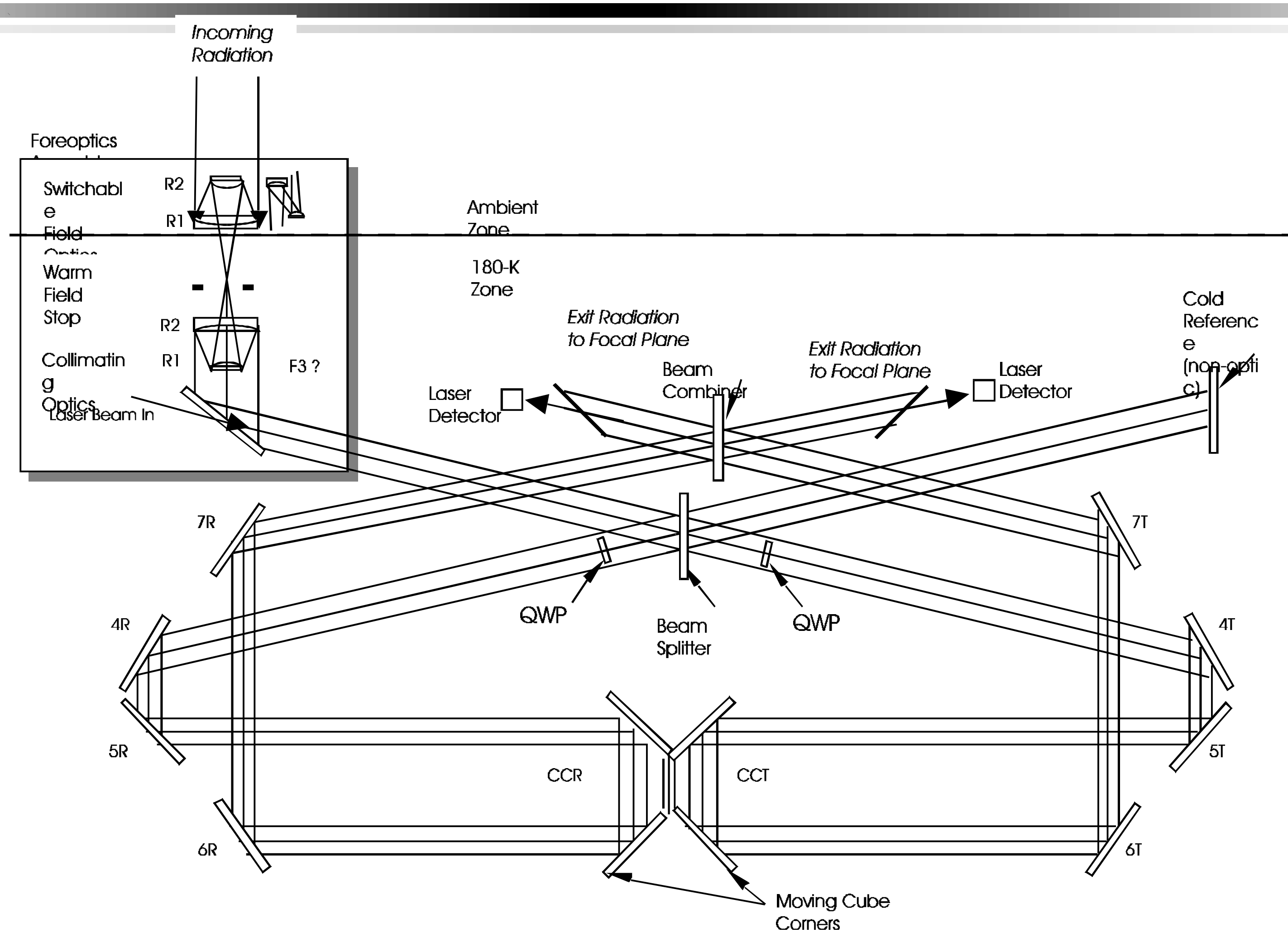
Pointing Control Subsystem Requirements

- Spacecraft Knowledge
  - Spacecraft/instrument attitude must be known to 0.375 mrad (1.3 arcminutes) in pitch and roll, and to 0.75 mrad (2.6 arcminutes) in yaw. The angle between the "actual" and the "reconstructed, after ground processing" pointing direction shall be better than 0.75 mrad (2.6 arcminutes).
- Boresight Definition
  - The pointing location of the instrument boresight (optical axis TBR) shall be derived from spacecraft navigation base. ***TBD reference to GIRD.***
- Boresight Knowledge
  - The angle between the "TES optical boresight" and the "alignment cube on the spacecraft" shall be known to better than TBD. ***TBD reference to GIRD***.

PCS Subsystem Requirements

- Accuracy
  - The angle between the "actual" and the "desired" pointing direction shall be better than +/- 1 pixel (1.5 mrad or 5.2 arcminutes).
- Stability
  - The variation in the pointing angle over a period of 49.2 seconds shall be 0.75 mrad (2.6 arcminutes), with a goal of better than 0.75 mrad for 250 seconds.
- Slew Rate
  - The pointing shall be able to slew from nadir to limb in less than 6.5 seconds.
- Jitter
  - Jitter amplitude shall be no worse than 0.075 mrad (10% of pixel) in any 4-second interval.
- Spacecraft Jitter
  - The instrument shall not correct for spacecraft-induced jitter, up to a frequency.

TES Optical Design



Interferometer Subsystem

- Folded Connes Interferometer
- Back to back retroreflectors move at 1.05 cm/sec
- Data acquisition time is either 4 or 16 seconds.
- Reverse direction in 0.6 seconds
- Complete Data take requires four 4 second observations (two of a calibration target, and two in nadir and three 16 second observations of the limb.
- Instrument stares at either the limb or a ground position during the entire period.
- The interferometer produces the main mechanical disturbance from the instrument. A waiver from the GIRD periodic disturbance torque requirement may be needed. The design isn't far enough along to be sure.

Focal Plane Subsystem

- Detector Arrays
  - 4 detector arrays required to optimize instrument performance over the spectral range.
  - 16 pixels provide simultaneous ground through tropopause measurements in the limb view.
- Focal Plane Optical Filters
  - cold filters required to control instrument noise bandwidth.

TES Focal Planes

- Detector Arrays 1 x 16 Pixels, each 1:10 aspect ratio
- Pixel Size 50 x 500 microns
- Pixel Pitch 60 microns (nominal)
- Wavelength Coverage
  - 1A 2.3 - 5.6 microns
  - 2A 5.3 - 9.1 microns
  - 1B 8.3 - 12.5 microns
  - 2B 11.1 - 15.4 microns
- Operating Temperature: 65 K

Cryocooler Subsystem

- Two Stirling cycle coolers
- One for each dewar
- Largest power consumer in the instrument
- Mounted on upper tray
- Radiate to earth
- On continuously
- Will probably have to turn off periodically to decontaminate cold finger

Calibration Subsystem

- Two Calibration Sources
- Radiometric Calibration Target
  - 180 - 350 K
  - Cylindrical Black Body
- Geometric Alignment Target
  - Projects point or line source onto focal plane array

Laser Subsystem

- Laser is a diode pumped Nd:YAG (1.06 microns)
- Output power 10 mw, Input Power < 10 W
- Laser is used for measurement of optical path length changes inside the interferometer
- No high voltages (< 24 v)
- No operational safety hazards during integration

Command and Data Handling Subsystem

- VME Bus based system
- RH6000 Computer
- 1553 Bus for Command/Telemetry
- High Rate Data Buffer/Formatter
  - TAXI interface to spacecraft
  - Compatible with all GIRD Requirements

Mechanisms, Structure and Thermal Subsystem

- Instrument Configuration and Interfaces
  - Defined in Instrument Description Document (IDD)
- Exceptions and specific Requirements
  - Defined in Unique Instrument Interface Document (IDD)

Mechanisms, Structure and Thermal Subsystem

- Spacecraft Interface
  - The TES thermal design shall meet all thermal requirements defined in the GIRD.
- Internal Temperature Regions
  - There shall be 3 designated internal temperature regions:

1) "nominal" at 270K
2) interferometer at 180K
3) detectors and filters 65K

- Power Dissipation
  - The TES thermal control design shall be able to dissipate 290W average power.

Mechanisms, Structure and Thermal Subsystem

- Mechanisms
  - Earth Shade
    - Can be opened and closed on command
    - We expect closings to be rare, if ever
    - Rate will be determined by GIRD torque limit spec
  - Gimbal
    - Described under PCS
    - Gimbal also is instrument aperture cover.
    - Calibration Position provides labyrinth seal
    - Moves frequently during operation
    - Low mass, low speed

Mechanisms, Structure and Thermal Subsystem

- Field Switch
  - Moves between limb and nadir observations
  - Two position changes in every 80.3 seconds
  - Low mass, should not be a torque problem
- Interferometer
  - Described earlier
- Cryocooler
  - Described earlier
- Filter Wheel
  - Rotates approximately 1/8 turn in 0.6 seconds in between data collections
  - Low mass, should not be an external torque problem

Power Subsystem

- GIRD compatible
- Supports three bus power interfaces, quiet, noisy, survival heater
- Cryocooler Subsystem is the only subsystem on the noisy bus
  - Cooler EMI may exceed the GIRD specification and require a waiver
- TES Power Subsystem is mostly COTS

Resource Requirements

TES Design Allocations

- TES instrument design is compatible with all Chemistry platform resource design allocations
  - Mass 290 kg
  - Power 275 W average
  - Volume 1.3m x 1.46m x 1 m
  - Data Rate 6.2 MBPS (peak)
- TES is compatible with all GIRD requirements and the Instrument Description Document

Development Schedule

TES Schedule

SCR	11/96
Phase C/D Start	12/96
PDR	2/98
Flight Hardware Start	3/98
EM Integration Start	7/98
CDR	2/99
PF Integration Start	6/99
PER	12/99
Environmental Test	12/99
Calibration Start	1/00
PSR	12/00
Deliver to S/C	1/01